

THE CONSEQUENCES OF THE COSMIC STAR-FORMATION RATE: X-RAY NUMBER COUNTS

A. PTAK¹, R. GRIFFITHS

Carnegie Mellon University, Dept. of Physics, Pittsburgh, PA 15213

N. WHITE

NASA/GSFC LHEA, Greenbelt, MD 20771

P. GHOSH

Tata Institute of Fundamental Research, Bombay 400 005, India

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ABSTRACT

We discuss the observable consequences for the detection of galaxies in the X-ray bandpass resulting from a peak in the cosmic star-formation rate at a redshift > 1 . Following White & Ghosh, we assume a large evolution in the X-ray/B luminosity ratio at $z \sim 0.5 - 1.5$ resulting from the X-ray binaries that have evolved from stars formed at $z > 1 - 2$. Using the HDF-N redshift survey data and the locally observed X-ray/B luminosity ratio as a guide, we estimate a median X-ray flux (2-10 keV) on the order of 8×10^{-18} erg cm⁻² s⁻¹ for galaxies in the HDF-N, which is consistent with a signal derived from a stacking analysis of the HDF-N Chandra data by Brandt et al. (2001). We also predict the number counts in deep X-ray surveys expected from normal galaxies at high redshift.

Subject headings: evolution-galaxies:evolution-X-rays: galaxies-X-rays

1. INTRODUCTION

The X-ray emission of nearby normal spiral galaxies has been observed to be dominated by X-ray binaries (XRB; see Fabbiano 1989 for a review). There is a strong correlation between the optical and X-ray luminosities of galaxies which is also consistent with an XRB population dominating the X-ray emission (i.e., assuming that XRB constitute an constant fraction of stars in a galaxy). Deep optical, IR and sub-mm surveys suggest that the peak of the cosmic star-formation lies at redshifts on the order of 1-2 or more (Blain et al. 1999). White & Ghosh (1998, hereafter WG98) predicted that X-ray binaries that form from this early star-formation activity should result in the enhancement of X-ray emission in galaxies, most notably around a redshift of 0.5-1.0 as the massive stars supernova forming low-mass X-ray binaries (LMXRBs) containing neutron stars. or blackholes The LMXRBs containing neutron stars in turn evolve to form millisecond radio pulsars (MRP), resulting in the observed distribution of XRB and MRP in the Galaxy and nearby galaxies. Further modeling by Ghosh & White (2001; hereafter GW01) has been undertaken to refine their previous results, with the primary improvement being the use of more recent star-formation rate (SFR) history estimates (e.g., Blain et al. 1999). These more recent SFR history estimates take into account sub-mm data which is sensitive to dusty (and hence obscured) high-redshift galaxies that would be missed by optical/UV surveys. The main impact of these modifications is that the current estimate of the enhancement of X-ray flux from galaxies (due to LMXRB) peaks at $z \sim 1.5$ rather than $z \sim 1.0$. The modeling of WG98 and GW01 also includes the predictions for enhancements of high-mass X-ray binaries (HMXRB). We defer evalu-

ation of the HMXRB enhancement for future work, but note here that since HMXRB have a much shorter evolutionary time scale than LMXRB, the HMXRB enhancement (along with other effects of starburst activity) would closely track the SFR history and therefore occur at higher redshifts than the LMXRB enhancement discussed here.

A test of these X-ray evolution models would be to evolve the local universe X-ray luminosity function and derive the number counts of galaxies expected at given flux levels (i.e., in a logN-logS diagram) for comparison with deep X-ray surveys. Unfortunately, the X-ray luminosity function of nearby galaxies is not known directly because the typical X-ray flux of galaxies is of order of $\log F_X = -13 - -14$ ergs cm⁻² s⁻¹ which is below the limiting flux of existing X-ray all-sky surveys (e.g. the ROSAT All-Sky Survey has a limiting flux on the order of $\log F_{0.5-2.0\text{keV}} \sim -12 - -13$ ergs cm⁻² s⁻¹; Voges et al. 1999). Here we take an alternative approach which is to use the known X-ray/optical luminosity correlation given in David, Jones & Forman (1992), determined from Einstein data, to estimate the X-ray luminosities and fluxes of galaxies in the HDF-N, where optical luminosities and redshifts have been established. Since the expected X-ray flux of high-redshift galaxies is low, Brandt et al. (2001) performed a stacking analysis of a *Chandra* observation of the HDF-N. We show below that the X-ray flux distribution derived from our analysis is consistent with the galaxy flux signal detected by *Chandra*. A secondary goal of this paper is to estimate the logN-logS distribution of galaxies (based on the HDF-N) in order to predict X-ray number counts that could be detected by more sensitive surveys.

2. METHODOLOGY

¹ Present address: The Johns Hopkins University, Dept. of Physics and Astronomy, 3400 N. Charles St., Baltimore, MD 21218; ptak@pha.jhu.edu

As discussed above, our main goal is to estimate the X-ray flux and luminosity for galaxies based on their optical luminosity, the X-ray/optical luminosity correlation and X-ray luminosity evolution models. The HDF-N “proper” sample presented in Cohen et al. (2000) contains redshifts and R-magnitudes for 125 galaxies spanning 4.75 arcmin². The X-ray/optical correlation given in David, Jones & Forman (1992) is based on B-band luminosities, so accordingly the observed R-band magnitudes must be converted to rest-frame B-band magnitudes. We used the k-correction plots in Frei & Gunn (1994) which include R to B band corrections based on optical and UV observations of galaxies (which we caution only extends to $z=0.6$), from which we derived the B-band luminosity for each galaxy (we used $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.1$ throughout this paper). Here we are primarily interested in the mean properties of galaxies and accordingly did not segregate by galaxy type, which we defer to future work (see also below). The k-corrections as a function of galaxy type vary by ~ 1 magnitude, which is somewhat larger than the scatter found for control galaxies by Frei & Gunn (1994), and accordingly we assume an uncertainty of 1 magnitude.

These B luminosities were then converted to X-ray luminosities using the $L_{0.5-4.5 \text{ keV}}/L_B$ relation given in David, Jones & Forman (1992). Assuming a power-law spectrum with a photon index of 1.8 and neutral absorption $N_H < 10^{21} \text{ cm}^{-2}$ (the galactic column towards the HDF-N is $1.6^{+0.2}_{-0.1} \times 10^{21} \text{ cm}^{-2}$; Stark et al. 1992), which is consistent with an XRB-dominated spectrum and the observed 2-10 keV X-ray spectra of nearby galaxies (c.f., Ptak et al. 1999 and references therein), $F_{2-10 \text{ keV}} = F_{0.5-4.5 \text{ keV}}$ to within $\sim 15\%$. Similarly, these same spectral assumptions also imply a $F_{0.5-2.0 \text{ keV}}$ flux that is $\sim (0.5 - 0.6)F_{0.5-4.5 \text{ keV}}$ (at redshifts exceeding 0.5, $F_{0.5-2.0 \text{ keV}} = 0.55F_{0.5-4.5 \text{ keV}}$ for all $N_H < 10^{21} \text{ cm}^{-2}$) and we adopt 1.0 and 0.55 as the conversion factor to the 2.0-10.0 keV and 0.5-2.0 keV bandpasses. We also note that the stellar evolution models we are concerned with here are relevant only on long look-back time scales, and therefore only the lower-mass, older stellar populations have a significant impact in our analysis. Ignoring the younger stellar populations biases our results in the sense of underestimating the expected X-ray flux for starburst systems which tend to exhibit enhanced supernovae and high-mass X-ray binary populations (see Fabbiano 1989). Since the David, Jones & Forman (1992) correlation was performed using all galaxies types, the differing amount of X-ray production as a function of galaxy type inherently contributes to the scatter of the correlation. Accordingly, the results of this paper should be accurate in a statistical sense but should not be applied to any individual galaxy.

The resultant B and X-ray luminosity distributions derived from this procedure are shown in Figure 1. The errors given in this figure are derived from a Monte-Carlo approach in which the conversion to the B and X-ray bandpasses was repeated (1000 iterations) with gaussian deviates with a standard deviation of 1 magnitude added to the resultant B magnitudes and gaussian deviates with standard deviation of 1 added to the log X-ray luminosities (i.e., simulating an order-of-magnitude scatter in L_X/L_B). Errors derived in this way were comparable to the counting errors that would be expected in each histogram bin

(i.e., \sqrt{N} , where N = the number of galaxies in a given histogram bin). The mean galaxy $L_{2-10 \text{ keV}}$ is $3.8 \times 10^{39} \text{ erg s}^{-1}$, which is comparable to the mean value for passive galaxies given in Georgantopoulos, Basilakos, & Plionis (1999) of $3.2 \times 10^{39} \text{ erg s}^{-1}$ (after adjusting to our values of H_0 and q_0). These values are somewhat lower than other nearby galaxies X-ray luminosity estimates (e.g., Fabbiano, Trinchieri, & McDonal 1984) however it should be noted that here and in Georgantopoulos, Basilakos, & Plionis (1999) active (including narrow-line) and starburst galaxies have not been (explicitly) included in the analyses.

2.1. Evolution in L_X/L_B

We proceed now assuming that the ratio L_X/L_B evolves as a result of an excess of X-ray binaries at earlier epochs. We use the evolutionary models “Peak-M” and “Gaussian” given in Ghosh & White (2001), plotted in Figure 2. Both models are based on fits to the observed star-formation rate using optical/UV observations, however the “Gaussian” model also includes a component with a Gaussian functional form that takes into account the evolution of the IR luminosity function using IR and sub-mm data (c.f., Blain et al. 1999). These models only take into account the relative change in X-ray luminosity as a function of redshift, however in this paper we are attempting to derive the X-ray luminosities of galaxies based on the rest-frame B-band luminosity. Accordingly, any optical evolution must be taken into account explicitly before we could apply our X-ray evolution models. To this end, we took the mean and standard deviation of the B-band luminosities in redshift bins large enough to contain at least 20 galaxies and fit $\log L_B$ as a function of z with a linear model (also shown in Figure 2). The X-ray luminosities were evolved by multiplying them by the ratio $E_X(z)/E_B(z)$, where $E_X(z)$ and $E_B(z)$ are the X-ray and optical (after normalizing to $z=0$) evolution models shown in Figure 2. The net amount of optical evolution derived in this way amounts to only a factor of ~ 2 from a redshift of 0 to 1.

3. RESULTS

Applying these procedures, the mean 2-10 keV X-ray galaxy flux increased from $2.3 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$ to 4.2 and $8.4 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$ and the mean 2-10 keV X-ray luminosity increased from $3.8 \times 10^{39} \text{ erg s}^{-1}$ to 5.3 and $19. \times 10^{39} \text{ erg s}^{-1}$ for the “Peak-M” and “Gaussian” models, respectively (with 0.5-2.0 keV values a factor of 0.55 lower as discussed above). The distribution of L_X and F_X (before and after including evolution) is shown in Figures 1 and 3. The flux density implied is 4.3 and $7.8 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ deg.}^{-2}$ in the 0.5-2.0 keV and 2-10 keV bandpasses, or 2-4% of the 2-10 keV X-ray background. Kuntz, Snowden & Mushotzky (2001) find that the extra-galactic X-ray background in the 1-2 keV bandpass is $\sim 5.7 \times 10^{-12} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ deg.}^{-2}$. With same spectral assumptions discussed above, $F_{1-2 \text{ keV}} \sim 0.3F_{0.5-4.5 \text{ keV}}$, implying a 1-2 keV flux density of $\sim 2.3 \times 10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ deg.}^{-2}$, or $\sim 4\%$ of the observed 1-2 keV background. We repeated our analysis after only including galaxies with redshifts in the range of 0.5-1.0 (55 galaxies) which resulted in a mean 2-10 keV X-ray flux of $\sim 7.0 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1}$ (indicating that our results are

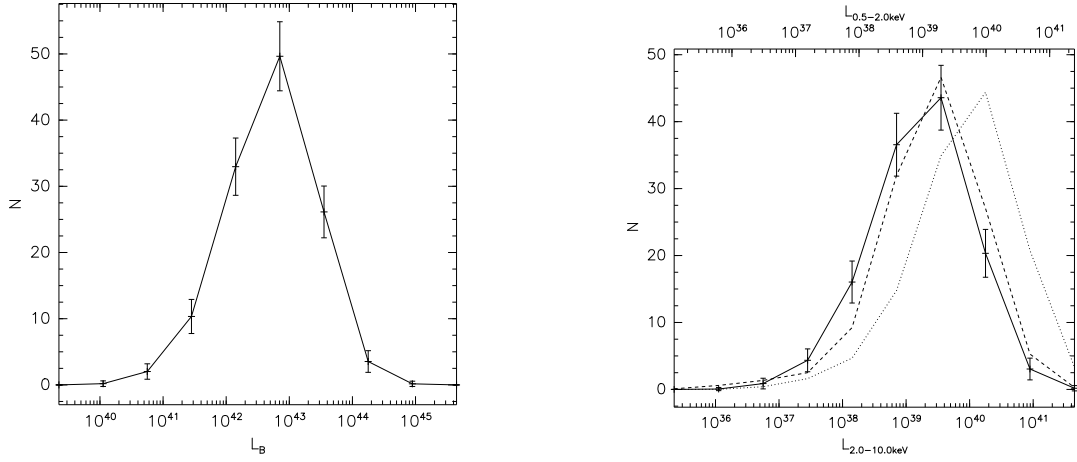


FIG. 1.— The estimated B-band (left) and X-ray luminosities (right) for the HDF-N galaxies. The error bars shown are derived from simulations that incorporate a 1 magnitude uncertainty in the k-corrections and an order of magnitude uncertainty in the X-ray/optical flux ratio. The X-ray luminosity distribution is given for the unevolved case (solid line and points) as well as that derived from the “Peak-M” (dashed line) and “Gaussian” (dotted line) evolution models.

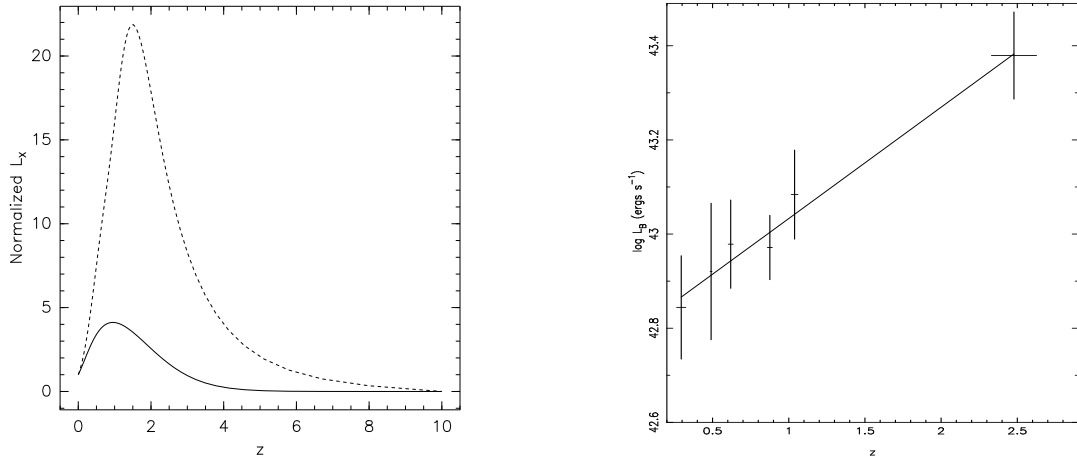


FIG. 2.— (left) Evolution models “Peak-M” (solid line) and “Gaussian” (dashed line) for the X-ray luminosity of normal galaxies, normalized at $z=0$, from Ghosh & White (2001). (right) Observed evolution in mean B-band luminosity for the HDF-N galaxies, with the linear fit to $\log L_B$ versus z plotted as a solid line. The error bars shown were derived by the dispersion of luminosities in each redshift bin.

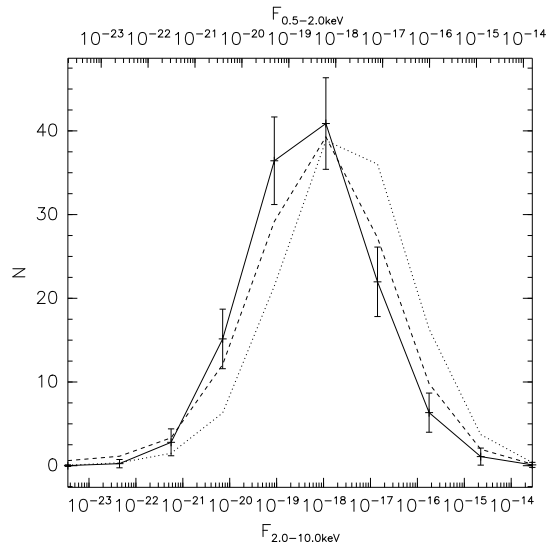


FIG. 3.— 0.5-2.0 keV and 2-10 keV flux distributions predicted for HDF-N galaxies. The lines and errors are defined as in Figure 1.

dominated by galaxies in this redshift range).

We proceed now to the question of the numbers of galax-

ies expected to be detected as a function of flux in ultra-

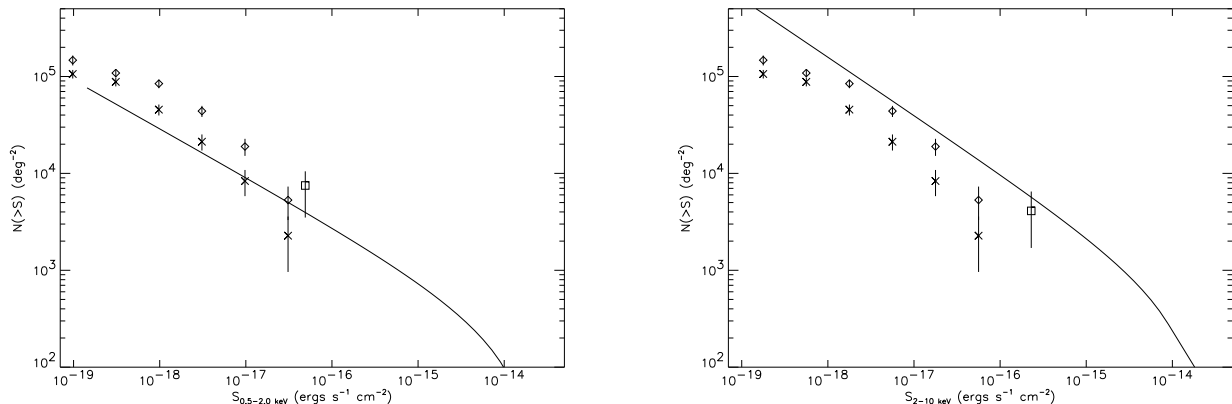


FIG. 4.— The logN-logS for galaxies derived from the HDF-N estimates for the “Gaussian” (diamonds) and “Peak-M” evolution models in the 0.5-2.0 keV (left) and 2.0-10.0 keV (right) bandpasses. The solid lines give the logN-logS double power-law fit from Tozzi et al. (2001) based on the Chandra observation of the HDF-S (note that this logN-logS includes all contributions to number counts). The square points mark the source density determined in the 500 ks Chandra HDF-N observation (Brandt et al. 2001). $F_X = 10^{18}$ erg cm $^{-2}$ s $^{-1}$ corresponds to $R \sim 24$.

deep *Chandra*, *XMM-Newton*, or future X-ray surveys. To address this, we derived the “logN-logS” number count distribution (i.e., the number of galaxies exceeding flux S as a function of flux) implied by our analysis, shown in Figure 4, using the HDF-N area cited above. The galaxy number counts have been corrected for spectroscopic completeness using Figure 1 from Cohen et al. (2000). This figure also shows the fits to the 0.5-2.0 keV and 2-10 keV HDF-S logN-logS distributions (Tozzi et al. 2001) (note that these curves are extrapolations below fluxes of $\sim 10^{-16}$ and 10^{-15} ergs cm $^{-2}$ s $^{-1}$ for the soft and hard bands, respectively). The 2-10 keV HDF-S logN-logS in the $S = 10^{-15} - 5 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$ range is in good agreement with the HDF-N logN-logS curve given in Garmire et al. (2001), where fluctuation analysis implies that the logN-logS curve flattens somewhat below $S = 1.0 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$. The total (i.e., including AGN) source densities determined by Brandt et al. (2001) are marked which also implies a flattening of the X-ray logN-logS. Note that the results of the stacking analysis in Brandt et al. (2001) cannot be plotted on this diagram since by design the analysis was done around optically-detected galaxies without significant X-ray counterparts and hence the area is not well defined. Depending on the amount that the AGN logN-logS flattens, the total X-ray logN-logS may become dominated by normal galaxies at fluxes below $\log F_X = -17 - -18$ erg cm $^{-2}$ s $^{-1}$, particularly in the soft band.

4. DISCUSSION

We have estimated the X-ray fluxes of galaxies in the Hubble Deep Field using the known X-ray/B-band luminosity correlation and taking evolution in the X-ray binary population of the galaxies into account (using the “Gaussian” and “Peak-M” models in GW01). Here we are only attempting to estimate the LMXRB contribution to the galaxy fluxes, which should dominate the X-ray fluxes unless significant starburst and/or AGN activity is present. The mean 2-10 keV X-ray flux that the Gaussian model predicts is $\sim 8.2 \times 10^{-18}$ erg cm $^{-2}$ s $^{-1}$ which can be compared with $\sim 1.7 \times 10^{-17}$ erg cm $^{-2}$ s $^{-1}$ obtained from a stacking analysis of a 500 ks *Chandra* observation of the

HDF-N (converted to the 2-10 keV bandpass from a signal of 2.3×10^{-17} erg cm $^{-2}$ s $^{-1}$ in the 0.5-8.0 keV bandpass assuming the same spectrum as discussed above) determined by Brandt et al. (2001). The “Peak-M” model predicts a mean X-ray flux a factor of ~ 3.5 lower than the “Gaussian” model. The “Gaussian” model is therefore predicting a signal which is a factor of ~ 2 less than the signal observed, although we note that Brandt et al. (2001) selected optically-bright galaxies (a sample of 11) for their stacking analysis, and our estimate of the mean galaxy X-ray luminosity (prior to the application of any evolution) is evidently somewhat lower than that assumed by Brandt et al. (2001) but is nevertheless consistent with other estimates. In both the hard and soft bandpass, we are predicting that galaxies make up $\sim 4\%$ of the X-ray background down to a flux of $\sim 10^{-18}$ ergs cm $^{-2}$ s $^{-1}$.

The best test of these models would be the direct detection of high- z galaxies in the X-ray bandpass, obviously with sufficient spectroscopic identification to rule out an AGN contribution to the X-ray flux. This would require an X-ray detection sensitivity on the order of 10^{-17} erg cm $^{-2}$ s $^{-1}$, which would imply an exposure on the order of 10 Ms for *Chandra* (i.e., the effective exposure in the stacking analysis was 5 Ms), while even such a large exposure would be insufficient for *XMM-Newton* to reach these detection sensitivities (due to *XMM-Newton* becoming background-limited at very large exposures). Optical (and, to a lesser extent, IR) spectroscopic identifications could possibly miss highly-obscured AGN or low-luminosity AGN which would produce enhanced X-ray fluxes relative to normal galaxies. A simple expectation is that the X-ray emission of galaxies would be extended (on spatial scales comparable to the optical emission), while the X-ray image of galaxies dominated by AGN would of course be unresolved. The half-light radius of galaxies in the HST Medium Deep Survey was typically $\sim 0.1 - 1.0''$, with a median value around $0.6''$ (Ratnatunga, Griffiths, & Ostrander 1999). Arcsecond resolution will therefore be necessary to detect any extension to galaxies.

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